

Hydrogen-loosing planets in transition discs around young protostars

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ABSTRACT

We point out that protoplanets created in the framework of the Tidal Downsizing (TD) theory for planet formation play a very important role for the evolution of accretion discs hosting them. Since all TD protoplanets are initially as massive as ~ 10 Jupiter masses, they are able to open very deep gaps in their discs, and even completely isolate the inner disc flows from the outer ones. Furthermore, in contrast to other planet formation theories, TD protoplanets are mass donors for their protostars. One potentially observable signature of planets being devoured by their protostars are FU Ori like outbursts, and episodic protostar accretion more generally, as discussed by a number of authors recently.

Here we explore another observational implication of TD hypothesis: dust poor inner accretion flows, which we believe may be relevant to some of the observed mm-bright transitional discs around protostars. In our model, a massive protoplanet interrupts the flow of the outer dust-rich disc on its protostar, and at the same time looses a part of its dust-poor envelope into the inner disc. This then powers the observed gas-but-no-dust accretion onto the star. Upon a more detailed investigation, we find that this scenario is quite natural for young massive discs but is less so for older discs, e.g., those whose self-gravitating phase has terminated a fraction of a Million year or more ago. This stems from the fact that TD protoplanets of such an age should have contracted significantly, and so are unlikely to loose much mass. Therefore, we conclude that either (i) the population of “transition discs” with large holes and dust-poor accretion is much younger than generally believed; or (ii) there is a poorly understood stage for late removal of dust-poor envelopes from TD planets; (iii) another explanation for the observations is correct.

1 INTRODUCTION

In the standard paradigm for planet formation (e.g., Wetherill 1990) and chapters 4-6 in Armitage (2010), large and massive protostellar discs eventually evolve into much less massive “protoplanetary” discs. The latter represent the end phase of star formation and the beginning phase of planet formation. Such discs can be now observed around nearby pre-main sequence stars (see, e.g., Dullemond & Monnier 2010, for a recent review).

An especially interesting sub-class of protoplanetary discs are the so-called “transition discs”, broadly defined as objects showing mid-IR excess above the protostar’s emission, but lacking the corresponding near-IR excess. Near-IR emission is characteristic of the inner \lesssim few AU disc region, and mid-IR emission is a signature of the outer \sim tens of AU disc. Therefore, transition discs are interpreted as protoplanetary discs with inner holes. High-resolution sub-millimetre continuum images of several sources, such as LkH α 330 (Brown et al. 2008) and GM Tau (Hughes et al. 2009), indeed show sharp inner holes tens of AU in radius

and thus confirm validity of this interpretation of spectral energy distributions (SEDs) of transition discs.

Since gas discs around protostars disappear with time, discs with inner holes are believed to be the discs that are at the beginning of their “disc clearing stage”. Since the fraction of such systems is low, e.g., ~ 0.1 of the sample, this was taken to mean that the transitional disc phase takes $\sim 10\%$ of the disc lifetime, e.g., from $\sim 10^5$ yrs to a few times that (Andrews & Williams 2005, 2007). Such a behaviour naturally appears in models in which the disc is first evolving on a long viscous time scale and is then photo-evaporated rapidly when the accretion rate drops to low $\sim 10^{-10}$ M_{\odot}/yr values (Clarke et al. 2001; Alexander et al. 2006).

It then came as a considerable surprise that transition discs with large $R > 15$ AU to ~ 70 AU holes are quite common among *mm-bright discs*: recent observations of Andrews et al. (2011) show that these discs comprise between 1/5 to $\sim 2/3$ of their sample of such objects. These massive discs should not really be the ones in the process of dispersal yet. The disc photo-evaporation models cannot easily create such large inner holes for the high accretion rates observed (see Owen et al. 2012). Therefore,

Owen & Clarke (2012) suggest that “... either (i) “transition discs” are a misnomer and these objects do not physically represent an evolutionary stage from disc-bearing and disc-less systems; or (ii) discs with inner holes can have multiple physical origins and the two populations shown in the data indicate two distinct classes of objects.”

The consensus seems to be building up to blame one or several massive planets per parent star, rather than disc photo-evaporation, for creating the observed gaps in the transition discs with large gaps (Andrews et al. 2011; Zhu et al. 2012). Physically, a giant planet of a few Jupiter mass or heavier pushes the gas away radially from its location by applying gravitational torques on the disc (Lin & Papaloizou 1986). This interaction first opens a wide gap in the protoplanetary disc. The inner disc then drains onto the protostar while the outer is held off by the planet; this results in a completely evacuated inner hole in the disc (Rice et al. 2003), potentially explaining the observations of large holes in transition discs.

However, many of the transition discs with inner holes have large *gas* accretion rates onto the protostar, e.g., up to $\sim 10^{-8} M_{\odot}/\text{yr}$, requiring that only the dust flow was interrupted by the planet but not that of the gas (Andrews et al. 2011). One plausible way out of this is a combination of dust filtration on gap edges and dust growth in the inner disc (Zhu et al. 2012). In particular, Rice et al. (2006) showed that since gas pressure gradient at the outer edge of a gap opened by a massive planet is positive, rather than negative in a disc without a gap, grain particles migrate outward in the frame comoving with the gas. This contrasts with the usual situation when dust grains migrate inward. The outward migration speed depends on the size of a particle and the properties of the gap, but generally large grain particles, e.g., those larger than ~ 1 mm migrate outward more rapidly than gas moves inward due to viscous torques. Therefore such particles are stopped effectively at the gap from penetrating the inner disc. However, smaller particles (smaller than about $10 \mu\text{m}$, see Rice et al. 2006) are so tightly bound to the gas by aerodynamical friction that they must follow the gas motion. These particles would follow the gas into the inner disc, through the gap, and would then still be observable in NIR, in contradiction to the observations (Andrews et al. 2011). To solve this difficulty, Zhu et al. (2012) propose that small dust particles that did penetrate the gap grow to large sizes, so that their opacity drops to barely detectable levels.

In this paper we propose a completely different take on the problem of dust-poor accretion onto the protostars, based on a crucial element of the new “Tidal Downsizing” scenario (TD; Boley et al. 2010; Nayakshin 2010a) for planet formation – *mass loss from the giant protoplanets*. This mass loss process is unique to TD scenario. The two other models for forming giant planets – the Core Accretion (CA) and the Gravitational disc Instability (GI) (see, e.g., Boley 2009), assume that planets always *grow* in mass by accretion of gas from the disc as they age. In both of these models the inner dust-poor disc must be a continuation of the larger scale accretion disc, perhaps modified by the presence of the planet as discussed above. In TD model, however, most of the protoplanets, having been formed in the outer cold disc at $R \sim 100$ AU, give their gaseous envelopes back to

the *inner disc* when they migrate sufficiently close to the parent star (see simulations by Cha & Nayakshin 2011).

In this paper we show that (i) TD planets, being initially more massive than CA planets, are able to open complete gaps in the protoplanetary discs. Therefore, in our model for transition discs with large inner cavities, the outer dust-rich accretion flow, in both gas and dust, is completely disconnected from the inner region. (ii) TD planets must lose their envelopes on the way to becoming the present day planets. The accretion flow inward of the gap can be “restarted” when these envelopes are accreted by the protostar (Nayakshin & Lodato 2012). In this picture, the protoplanet behaves like a lower mass version of the mass-losing secondary in a compact stellar binary system with mass transfer (e.g., Ritter 1988). (iii) Crucially, the envelopes of TD protoplanets are dust-poor (Nayakshin 2010a) because the dust is expected to sediment to their centres. Therefore, we propose that the inner accretion flow of dust-poor transition discs is nothing less than the planet’s envelope devouring stage of Tidal Downsizing for one of the inner planets.

Below we explore this model in greater detail.

2 PLANETS AND PROTOPLANETARY DISCS

2.1 TD model

The first suggestion that planets are initially much more massive than they presently are, was made, to the best of our knowledge, by Kuiper (1951), who proposed that planets grew from self-gravitating condensations in the Solar Nebula. His Figure 1 shows that he considered it quite possible that protoplanets were initially much more massive. Specifically, on page 9 on his manuscript he suggests that each of the Solar System planet was formed from ~ 0.003 Solar masses of gas and dust, a guess that, amazingly, is consistent with the TD model within a factor of a few. McCrea & Williams (1965) added practical detail to this scenario, explaining how the differentiation of materials within such proto-planets could have taken place. They showed that microscopic grains grow and sediment to the centre of such gas clumps within a few thousand years (cf. also Boss 1997). Proto-Earth formation in this picture is complete when the gas envelope of the proto-planet is removed by Solar tides.

However, since the process of planet migration was unknown until later (Lin & Papaloizou 1979; Goldreich & Tremaine 1980), a physically complete and self-consistent scenario for this *top-down* scenario for planet formation was not found, and the model was essentially given up (Donnison & Williams 1975) until very recently (Boley et al. 2010; Nayakshin 2010a). The modern version of the top-down scenario is essentially Gravitational disc Instability model for planet formation upgraded by the physics of giant planet migration and disruption. In the TD scenario, massive $\sim 10 M_J$ (e.g., Boley et al. 2010; Forgan & Rice 2011) gaseous clumps are formed in the outer disc by the disc’s GI. The clumps then migrate inward, while dust sediments to the centre of the clumps (Helled & Schubert 2008; Helled & Bodenheimer 2011; Nayakshin 2010b, 2011a). A partial removal of their gas

envelopes by gravitational tides, irradiation or other effects (Boss et al. 2002; Nayakshin 2010a; Nayakshin & Cha 2012) results in formation of metal-enriched giant planets such as Jupiter or Saturn, whereas a complete removal of the gas results in terrestrial like planets.

TD model has direct connections to protostellar disc evolution. A story line very similar to TD scenario, but minus the role of dust grains, has been developing in the field of protostellar evolution since Vorobyov & Basu (2006). These authors found that massive gaseous clumps formed by GI in the outer disc migrate rapidly inward and get “accreted” by the star in bursts (see also Vorobyov & Basu 2010). Such accretion bursts appear to be a natural explanation for the FU Ori outbursts of young protostars where the star accretes mass at rates as high as $\sim 10^{-4} M_{\odot} \text{ yr}^{-1}$ (Hartmann & Kenyon 1996). A detailed investigation of this episodic accretion model for the FU Ori outbursts by Nayakshin & Lodato (2012) confirmed its potential promise, and also showed that the inner disc behaviour may be additionally modulated by the thermal ionisation instability. This implies that both episodic accretion and thermal ionisation instability (Bell & Lin 1994) may play a role in explaining the observed FU Ori outbursts. The other side of this bursty accretion picture – long periods of relatively low protostellar accretion rates – may naturally explain (Dunham & Vorobyov 2012) the “luminosity problem” of young stars (Hartmann & Kenyon 1996).

2.2 Protoplanetary disc sculpting by TD planets

A sufficiently massive protoplanet may open a gap in the accretion disc and thus regulate the rate of mass flow onto the protostar (Lin & Papaloizou 1986). Crida et al. (2006) show with 2D simulations that the inner disc surface density is decreased by a factor of 10 (compared with a disc with no embedded planet) when the parameter $\mathcal{P} \equiv 3H/4R_H + 50/(\mathcal{R}q) \approx 1$, where $q = M_p/M_*$, R_H is the Roche lobe radius, $R_H = R(q/3)^{1/3}$, $\mathcal{R} = Rv_K/\nu$ is the Reynolds number, which can be re-written as $\mathcal{R} \approx (R/H)^2 \alpha^{-1}$ for the Shakura & Sunyaev (1973) disc model with viscosity parameter α and the disc vertical aspect ratio H/R . For $m_1 = M_p/(10M_J)$, and $H/R = 0.05$, we have

$$\mathcal{P} \approx \frac{1}{4m_1^{1/3}} + \frac{\alpha_2}{8m_1}, \quad (1)$$

where $\alpha_2 = \alpha/0.01$. Furthermore, the smaller the value of \mathcal{P} , the deeper the gap (the stronger the suppression of the inner disc). For $m_1 = 1$, for example, $\mathcal{P} \approx 3/8$. Such a massive planet opens an infinitely deep gap in the disc according to equation (13) of Crida & Morbidelli (2007), that is, the inner disc is completely cut off from the outer one by the planet. Equation 1 predicts, on the other hand, that $\mathcal{P} \approx 1$ for $M_p = 2M_J$, thus the gap is expected to be leaky, so that $\sim 10\%$ of gas is able to filter through to the inner disc (Crida et al. 2006). In accord with these results, Nayakshin & Lodato (2012) found that protoplanetary discs with $m_1 \sim 1$ protoplanets feature infinitely deep gaps, so that the inner disc empties out on the protoplanet and becomes devoid of any gas flow for a period of time.

Given these results, protoplanets are much more important for the evolution of protoplanetary discs in TD scenario than they are for discs with CA-built planets. Indeed, in TD

scenario, *every* protoplanet, including those that go on to eventually make “tiny” planets such as the Earth is initially quite massive, e.g., from a few to over $10 M_J$. In other words, *essentially every* planet before the downsizing step may be able to open a very deep gap in the TD scenario. Thus we expect discs with empty or very strongly depressed inner flows to be a much more frequent feature in the TD picture. If we accept that FU Ori outbursts are produced by giant protoplanets being torn into pieces and then accreted by their protostars, and that this happens $\sim 10 - 20$ times during assembly of a typical star (Hartmann & Kenyon 1996), we would expect that discs with inner holes/strong depressions should exist for a good fraction, e.g., one comparable to unity, of all mm-bright (that is massive) protoplanetary discs.

In addition to this, TD scenario planets not only open the gaps and thus hold off accretion of gas and dust beyond their orbits, they can also feed their protostars with a significant amount of matter, given their masses. To appreciate this, we note that the total mass of all the Solar System protoplanets in the CA framework is about 1.5 Jupiter masses, while in TD picture this is somewhere between 40 and 80 Jupiter masses (assuming that Solar System planets were built from gas embryos of mass between 5 and 10 Jupiter masses).

With this in mind, we echo the suggestion of Owen & Clarke (2012) that some transition discs may not represent systems where the discs are being removed. We suggest that the flow of matter in these discs, both in gas and dust, is temporarily interrupted by very deep gaps. While the outer disc is held off by one or more embedded planets (as suggested earlier by a number of authors, e.g., Rice et al. 2006; Zhu et al. 2012), the inner disc is fed by dust-poor gas lost by one or more planets in the gap.

In the simulations of Nayakshin & Lodato (2012), the period of the completely empty inner disc (zero accretion rate onto the protostar) ends when the protoplanet is pushed deep enough so that it fills its Roche lobe and starts losing the mass through the inner Lagrangian L1 point. The inner disc is then quickly re-filled *by the material lost by the planet* and accretes onto the protostar at very high accretion rate, leading to an FU Ori-like outburst. These simulations confirm the earlier suggestions by Vorobyov & Basu (2006); Boley et al. (2010) that tidal disruption of giant protoplanets may produce accretion outbursts with properties required to explain the FU Ori outbursts.

Below we consider whether a physically similar model may explain the Transition discs with *large* inner dust cavities. **To avoid potential confusion, we point out that the outer self-gravitating portions of relatively massive protoplanetary discs may have larger H/R than the value of 0.05 used in equation (1) above, so that the protoplanets manage to migrate in type-I regime there (e.g., Baruteau et al. 2011; Boley et al. 2010; Cha & Nayakshin 2011)** Although the transition in the migration regime of such massive protoplanets is a subject of ongoing research (S.-J. Paardekooper, private communication), the transition is generally expected to occur where the disc mass interior of the planet becomes comparable to that of the protoplanet, so that type-I migration rate slows down (see

also the physically related case of a binary super-massive black hole migration in Lodato et al. 2009).

3 STEADY STATE MASS LOSS FROM PROTOPLANETS

3.1 Terminology

We shall first consider steady-state scenarios – and will find them unlikely – in which the inner dust-poor accretion disc is in a quasi-steady state, so that the mass is deposited into the disc by the protoplanet at the same rate as it is accreted by the protostar. An example of such a situation is quasi-equilibria found in some of the Nayakshin & Lodato (2012) simulations.

In TD scenario, giant protoplanets go through two stages on the way to becoming fully fledged dense giant gas planets (Boley et al. 2010; Nayakshin 2010b, 2011b). The first stage begins with formation of the protoplanet in the outer cold disc by gravitational instability. The “first protoplanet” is a rather fluffy gas clump in which hydrogen is molecular; the clump’s central temperature is \sim hundreds of Kelvin and its radial extent is a few to ten AU. These clumps cool rapidly: within some 10^3 to at most 10^5 yrs (depending on the clump’s mass and grain opacity, see Helled & Bodenheimer 2011) the central temperature approaches $T \approx 2000$ K at which point hydrogen molecules dissociate rapidly, and the clump collapses hydrodynamically to sizes of the order of 0.03 AU or even smaller (cf. §3.4 in Nayakshin & Lodato 2012). This collapse begins the second stage in the protoplanet evolution, when most of hydrogen is atomic or partially ionised. This picture is very similar to the evolution from the first to second cores in star formation (Larson 1969), although here mass of the protoplanet may remain fixed during contraction and collapse. We shall thus call protoplanets dominated by atomic or ionised hydrogen “second planets” below for brevity.

3.2 Roche lobe overflow mass loss

Mass transfer from a Roche lobe-filling secondary to the primary has been a subject of numerous papers in the context of cataclysmic binaries (e.g., Ritter 1988). The secondary’s mass loss rate is found to be a very strong function of $\Delta r = r_p - r_H$ where r_p is the planet’s radius. Before the Roche lobe of the secondary is filled, $\Delta r < 0$, the mass transfer rate has an exponential form reflecting the exponential decrease of density with height in the stellar atmosphere (cf. eq. 9 of Ritter 1988):

$$\frac{dM_p}{dt} = -\frac{\rho_{\text{ph}} c_{\text{ph}} r_H h_p}{e^{1/2}} \exp\left[\frac{\Delta r}{h_p}\right], \quad (2)$$

where M_p is the planet’s mass, $h_p = kT_{\text{ph}} r_p^2 / \mu GM_p$ is the scale height of the planet’s atmosphere, μ is the mean molecular weight, here taken to be $2.3m_p$, T_{ph} , ρ_{ph} and c_{ph} are the photosphere’s density and sound speed, respectively. The Hill’s radius is given by

$$r_H = a(M_p/3M_*)^{1/3}, \quad (3)$$

where a is the planet-star separation. r_H is approximately equal to the Roche lobe radius.

Here we are interested in planets situated at $a \gtrsim 10$ AU. Nayakshin (2010b), using a simple $\kappa(T) \propto T$ dust opacity model for first protoplanets, obtains that at large time t since the formation of the clump, the clump’s radius is $r_p \approx 0.8 \text{ AU} (10^4 \text{ yr}/t)^{1/2}$, independently of the clump’s mass. Given the planet’s luminosity (see §3 in Nayakshin 2011a), we obtain planet’s photosphere – effective – temperature of about 100 K. The photosphere’s scale height is then very small compared to r_p ,

$$\frac{h_p}{r_p} = \frac{kT_{\text{ph}} r_p}{GM_p \mu} \approx 0.03. \quad (4)$$

This shows that unless r_p is almost exactly equal to r_H , the factor $\exp(\Delta r/h_p)$ is very small. Speaking qualitatively, the Roche lobe overflow rate is nearly zero when $r_p < r_H$ and then suddenly becomes very large (up to $\sim 10^{-4} M_\odot \text{ yr}^{-1}$) when $r_p > r_H$ (Nayakshin & Lodato 2012). It would thus be a surprising coincidence to have the planet to loose mass at the observed gas accretion rate range ($10^{-10} - 10^{-8} M_\odot \text{ yr}^{-1}$).

The arguments presented just above are for the first protoplanets. As we mentioned above, massive $\sim 10 M_J$ H_2 clumps survive only for \sim (few to few tens) of thousand years before collapsing to much denser second configuration. This is too short given that transition discs probably exist for $\sim 10^5$ years: finding a protoplanet in the first stage inside the transition disc cavity should be unlikely. The protoplanet may be inflated by tidal torques (Goldreich & Soter 1966) if its orbit is eccentric, but the relevant time scales (e.g., §3.2 in Bodenheimer et al. 2003) are longer than the Hubble time at $a \gtrsim 10$ AU.

The second stage protoplanets are much more compact than the first stage ones, so that the ratio h_p/r_p is yet smaller for them. We conclude that a quasi-steady state tidal disruption (Roche lobe overflow) of giant protoplanets is unlikely to match the observed protostellar accretion rates of transition disc systems.

3.3 Photo-evaporation of the second stage planets

Alternatively, planets may loose mass by photo-evaporation (Lecavelier Des Etangs 2007). However, Owen & Jackson (2012) showed that mass loss of the second stage planets due to photo-evaporation does not exceed $\sim 10^{-10} M_\odot \text{ yr}^{-1}$ even for planets located at distances as close as 0.1 AU from the star. The weight of the argument is best appreciated by considering the energy-limited photo-evaporation, which is essentially the maximum possible outflow rate in which all the ionising power goes into driving the outflow, with no re-radiation losses (see, e.g., Owen & Jackson 2012). The fraction of stellar radiation intercepted by the planet is $\zeta_{\text{rad}} = \pi r_p^2 / 4\pi a^2$, which is only ~ 0.0025 for a few M_J planet completely filling its Roche lobe. The combined X-ray and UV luminosity of a typical T-Tauri star is $L_{\text{ion}} \sim$ a few $\times 10^{30} \text{ erg s}^{-1}$. This yields the maximum outflow rate

$$\dot{M}_{\text{en}} \sim \frac{\zeta_{\text{rad}} L_{\text{ion}}}{c_{\text{ph}}^2} \simeq 10^{-10} M_\odot \text{ yr}^{-1}, \quad (5)$$

where $c_{\text{ph}} \sim 10 \text{ km s}^{-1}$ is the sound speed in the evaporated outflow. Since r_p is only a few percent of r_H for the second stage planets at $a \sim 10$ AU, we conclude that the photo-evaporative mass loss rate is completely inadequate to ex-

plain the observed gas accretion rates of up to $10^{-8} \text{ M}_{\odot} \text{ yr}^{-1}$ in the Andrews et al. (2011) sample.

3.4 Circum-planetary disc and its removal

Recently, Galvagni et al. (2012) demonstrated the importance of rotation for clumps formed in the outer gravitationally unstable disc during the transition from the first to the second protoplanetary stages. In particular, when H_2 dissociation occurs only $\sim 50\%$ of mass of the initial clump collapses into a quasi-spherical second planet, with the rest orbiting the collapsed part in a thickish ($H/R \sim 0.5$) rotationally supported circum-planetary disc. This disc (instead of the planet's atmosphere) could in principle play the role of the dust-poor mass reservoir being stripped away and consumed by the parent star.

Circum-planetary discs are truncated by tidal torques from the star at around $r_d \sim 0.3r_H$ to $0.4r_H$ (Ayliffe & Bate 2009; Martin & Lubow 2011). Thus their outer edges are still quite far from the L1 point. The most likely way to loose these discs is by photo-evaporation (Mitchell & Stewart 2011). However, applying the equation A7 in Adams et al. (2004) for the present case, the rate at which the discs are likely to be photo-evaporating is modest, $\dot{M}_d \leq 10^{-10} \text{ M}_{\odot} \text{ yr}^{-1}$. Furthermore, this is likely to be an over-estimate, since we find that H_2 molecule densities in the evaporative flows would be $\sim 10^9 \text{ cm}^{-3}$, and therefore the H_2 gas should self-shield itself from the FUV radiation (see the end of §2.1 and §2.3 in Adams et al. 2004), further reducing the estimate. Finally, the path of the protostar's photo-ionising radiation to the planet is likely to be blocked by the observed inner gas accretion flows since the inner disc aspect ratio ($H/R \sim 0.1$) may be larger than r_p/a . Therefore, while it appears clear that circum-planetary gas discs can be efficiently removed by photo-evaporation on long time scales (Mitchell & Stewart 2011), it seems that their steady-state mass loss is insufficiently large to explain protostellar accretion rates of up to $10^{-8} \text{ M}_{\odot} \text{ yr}^{-1}$.

4 NON-STEADY SCENARIOS

The accretion disc viscous time at radius R is

$$t_{\text{visc}} \sim \alpha^{-1} \frac{R^2}{H^2} \Omega(R)^{-1} = 5 \times 10^4 \text{ yr } \alpha^{-1} \frac{R^2}{100H^2} R_1^{-3/2}, \quad (6)$$

where $R_1 = R/10 \text{ AU}$, α is the Shakura & Sunyaev (1973) viscosity parameter, H/R is the disc geometrical aspect ratio, and $\Omega(R) = (GM_*/R^3)^{1/2}$ is the Keplerian angular frequency. The accretion disc viscous time is comparable with the estimated lifetime of the transition disc phase, suggesting that the disc may not necessarily be in a quasi-steady state. This in turn implies that the observed proto-stellar accretion rates do not have to be equal to *instantaneous* mass loss rates from the planet(s) in the scenario we propose.

Suppose that a massive gas planet has lost a $\Delta M \sim 1M_J$ of its dust-poor envelope. The average accretion rate onto the protostar as the result of this is

$$\langle \dot{M} \rangle \sim \frac{\Delta M}{t_{\text{visc}}} = 10^{-8} \frac{\text{M}_{\odot}}{\text{yr}} t_5^{-1}, \quad (7)$$

where $t_5 = t_{\text{visc}}/(10^5 \text{ yr})$. One expects that initially the accretion rate is higher than this estimate but then decays to

a somewhat lower value. Statistically speaking, one is more likely to catch the longer decaying part of this accretion episode, so that the range of the observed accretion rates in the Andrews et al. (2011) sample appears qualitatively natural in this picture.

To test these ideas, we have used the code of Nayakshin & Lodato (2012) to investigate the disc-planet system evolution in the case of a partial envelope or circum-planetary disc removal from a massive planet. In this calculation we assume that the planet opened a gap in the accretion disc and that the inner disc has drained onto the star before the calculation begins. We then assume that the planet quickly loses a set amount of its envelope through the L1 point into the inner disc and then simulate the longer term evolution of the disc-planet system.

Figure 1 presents one such calculation in which the initial mass and position of the planet is $M_p = 12M_J$ and $a = 40 \text{ AU}$, respectively. The initial disc surface density profile follows the form

$$\Sigma_0(R) = \frac{A_m}{R} \exp\left[-\frac{R}{R_0}\right] \quad \text{if } R > R_{\text{hole}}(0) \quad (8)$$

and $\Sigma_0(R) = 0$ for $R < R_{\text{hole}}(0) = 2a$, where $R_0 = 60 \text{ AU}$. The functional form used in equation 8 is the same as that used by Andrews et al. (2011) to fit their observations. The normalisation constant A_m is set by requiring the total disc mass to be $M_d = 0.03 \text{ M}_{\odot}$.

The planet's mass loss in this calculation is assumed to be constant during the first $t_0 = 10^4 \text{ yrs}$, $dM_p/dt = -\Delta M_p/t_0$, where $\Delta M_p = 3M_J$, and then $dM_p/dt = 0$ for $t > t_0$. This mimics an essentially instantaneous mass loss from the planet and its injection into the inner disc.

Initially the mass lost by the planet circularises in a ring at $R = a(1 - r_h/a)^4$ (cf. equation 38 in Nayakshin & Lodato 2012), just inward of the planet's location. It then spreads viscously in both directions. The inward facing front of this vspreading ring then starts accreting onto the star, whereas the outer edge starts to exchange the angular momentum with the planet. The strong gravitational torques in this model keep the inner dust-poor accretion flow separated from the outer dust-rich disc.

Figure 1a presents snapshots of the disc surface density profile at four different times as indicated in the caption. **We emphasise that the accretion flow inward of the gap (planet) is the flow of matter dumped by the planet into the inner disc, so it is physically distinct from the outer dust-rich disc flow.** As the planet is pushed closer to the star, the outer disc edges closer as well. The inner disc shrinks in size and mass with time. By the last snapshot shown in the figure (dotted curve), almost all of the planet's envelope has been accreted by the star. Shortly thereafter, the inner $\sim 10 \text{ AU}$ feature a complete disc hole – in gas and dust at the same time.

Figure 1b shows the planet-star separation evolution (solid curve) and the dust hole radius evolution with time (dotted). Fig. 1c shows the accretion rate evolution onto the protostar. As expected from our analytical estimate above, the accretion rate onto the protostar indeed spans the range from 0 to $\sim 10^{-8} \text{ M}_{\odot} \text{ yr}^{-1}$. Note that the dust hole size and the protostellar accretion rate are consistent in bulk with the observed mm-bright sample of Andrews et al. (2011) for

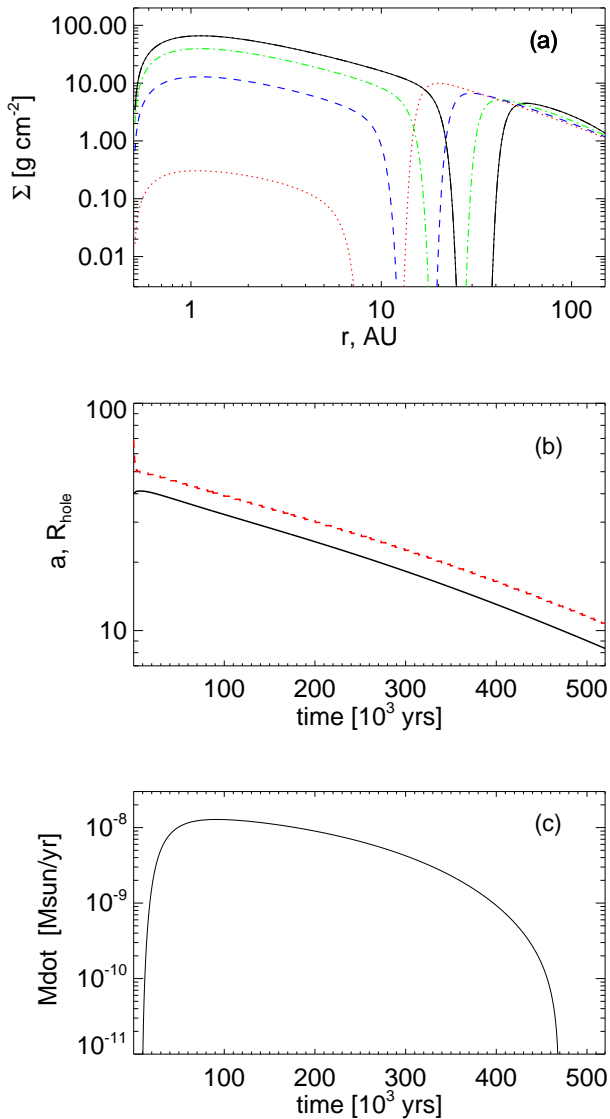


Figure 1. (a) Disc surface density profile $\Sigma(R)$ at times $t = 0.11, 0.23, 0.35$ and 0.46 Myr shown with the solid, dash-dotted, dashed and dotted curves, respectively. We emphasise that the material filling in the disc inward of the gap has been deposited there by the planet that lost its dust-poor envelope. The inner disc is physically distinct and separated by the gap from the outer disc. (b) The planet-star separation, a , and the size of the dust hole, R_{hole} , versus time, shown with the solid and dashed curves, respectively. (c) The protostellar accretion rate versus time.

~ 0.3 Myr, which appears to be long enough to account for the significant frequency of the discs with large holes.

5 DISCUSSION

In this paper we argued that protoplanets created in the framework of Tidal Downsizing scenario play a very important role for their protoplanetary discs, one much more important than do planets in the CA framework. Since a typ-

ical planet is initially as massive as ~ 10 Jupiter masses, TD scenario predicts that discs with deep gaps opened by gravitational torques of the planets must be much more frequent than in the CA picture. Furthermore, as shown by Nayakshin & Lodato (2012), such massive planet can (temporarily) completely stop the flow of gas and dust from the outer disc, which is not possible for any but only the most massive CA planets. Finally, TD planets may themselves feed inner accretion flows when their envelopes are removed by tides or other effects.

We then suggested that the current conundrum of the observed mm-bright transition discs with large *dust but not gas* holes is resolved by combining the de-facto most popular scenario for the hole opening – massive planet(s) inside the hole – with the TD ideas, e.g., that massive gaseous protoplanets have their dust sedimented and locked into the cores and their dust-poor envelopes removed by tides or other effects. We then found that steady-state mass loss from either “first planets” (molecular H_2) or “second planets” (atomic or ionised H) at the requisite rates of up to $\sim 10^{-8} \text{ M}_{\odot} \text{ yr}^{-1}$ is unlikely (§3). In brief, the first planets should cool too rapidly so are somewhat unlikely to be found in transition discs that are at least a fraction of a Myr old; the second planets are too compact to loose mass at the observed high rates.

However, in §4 we pointed out that the inner dust-poor flows inside the planet’s orbit do not have to be steady state on the disc viscous time scale, which is of the order of ~ 0.1 Myr at the observed dust edges (equation 6). In particular, it appears possible that the observed accretion rates onto the protostars in the transition discs are the residual flows remaining after a few M_J of dust-poor material was dumped by a planet into the inner disc. One interesting possibility that we shall pursue in a future paper is that such an episodic envelope removal from the planet is a consequence of a much larger X-ray and ionising flux from the protostar during the “last” FU Ori outburst of the protostar (the average steady-state fluxes do not result in large enough steady-state planet photo-evaporation, see §3).

One issue that requires future work is the exact mechanism through which protoplanets may loose the required amount of mass, which was simply postulated in our numerical calculation above. It is definitely easier for first stage planets to loose mass than it is for the more compact second stage ones. The first stage planets may however not live long enough for most of class II protostars. It may be possible that some of these are younger than they appear due to swelling during FU Ori outbursts (Baraffe et al. 2012). Also, the first stage protoplanets may be supported against contraction due to internal energy release in the manner discussed in Nayakshin & Cha (2012), and so may survive for longer than calculations neglecting the energy release at the core suggest (e.g., Nayakshin 2010a; Helled & Bodenheimer 2011).

Furthermore, there are other plausible ways in which the necessary dust-poor material can be lost by the planets inside the hole at the requested rates. If there is more than one massive planet inside the hole, their mutual interactions may drive secular evolution of the system, pumping planets’ eccentricities and/or changing their inclinations. One of the planets (or the circum-planetary disc around it) may then loose mass at each passage of the pericentre. The matter

lost by the planet would then accrete onto the star on much longer viscous time scales in a seemingly steady-state accretion.

We note that we did not consider here the photo-evaporation of the disc itself, a process which may influence the structure of the disc in additional ways (e.g., Rosotti et al. 2013).

6 CONCLUSIONS

We suggested that the process of dust sedimentation invoked in the Tidal Downsizing scenario for planet formation **potentially** provides an attractive explanation for the origin of the dust-poor accretion flows onto protostars in mm-bright transition disc systems. Since dust grows and sediments to the centre of TD protoplanets, their envelopes are dust-poor. To explain the fact that most planets are far less massive than the initial protoplanet mass of many Jupiter masses, these envelopes must be lost to the parent stars. It would thus be natural to find at least some protostars to accrete dust-poor matter. The expected accretion rate of protoplanet's envelopes onto the protostar in this picture is, within an order of magnitude, $\dot{M} \sim$ a Jupiter mass divided by $\sim 10^5 - 10^6$ yr (the order of magnitude disc viscous time and also the estimated age of the transition discs). This predicts a typical protostar accretion rate $\dot{M} \sim 10^{-9} M_{\odot} \text{ yr}^{-1}$, which is logarithmically in the middle of the observed accretion rates (Andrews et al. 2011).

However, one difficulty of our model is in the required age of the protoplanets. If the observed transitional discs are indeed ~ 1 Myr past the massive self-gravitating stage of the disc evolution, then the protoplanets embedded in them would have to be similarly old. At this "old" age they should have contracted to very high densities; it appears very hard for them to loose much mass by any of the mechanisms we considered in this paper. A resolution to this may be found if we over-estimate the age of the discs in these systems; we under-estimate the planet mass loss at a fraction of a Myr; or this model does not apply to the older of the observed systems.

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